Night Cooking Solar Cooker Using Molten Sodium Chloride as Phase Change Material

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***Abstract*— Solar cooking technology has to undergo a sea change if at all it's to be accepted as the main source of cooking Energy. This is why a better model that incorporates both the traditional heat trapping cum concentrator mechanism and the latest techniques like that which uses a solar battery (phase change materials with high heat retention capability) can be used as the basic idea for the purpose.**

A multi-purpose hybrid solar cooker using locally available materials can be used for night as well as day cooking. It will have two way supply of heat directly from sun during day time for cooking and from the phase change material during night time. This cooker preferably provides indoor cooking and it can have two arrangements, namely Grill and Oven, for cooking various Indian foods.

Sufficient care was taken for selecting the materials to be used in this solar cooker with price and availability constraints across rural India. The design ideally can cook two traditional meals a day for a family of five. All assumptions for the design are based on this basic aim.

I. INTRODUCTION

Solar cooking with all its benefits, starting from environment-friendliness to its cost effectiveness, is yet to be accepted as a viable option for cooking. The main reason for this can be traced out as;

1. Cooking occurs only in sunshine hours.

2. No ease of cooking as the user has to wait longer for simple cooking processes like boiling.

3. Limited number of dishes that can be cooked.

While in the day time cooking will not be an issue, for the night there has to be some form of back-up energy stored throughout the day. This is achieved by selecting a material that has high heat retention capability. However recent studies show that sensible heating is not the option, even if the material has a high Specific Heat. This is why we opted for Latent Heat storage using phase change materials. Latent heat storage is a relatively new area of research which can be used for storing heat by changing the phase of the material (phase change material-PCM) without rise in its temperature.

To improve the ease of cooking one must separate the traditional model of a solar cooker that has its absorber, cooking surface and heat storage system all jammed to the same place. We can implement the design by having an outdoor arrangement for heat absorption and storage that includes the Phase Change Material, a heat exchanger with water-glycol solution as its fluid which is regulated by a condenser and steam tank, and finally an indoor cooker installed inside the kitchen.

II. PRINCIPLE OF NIGHT-COOKING

The traditional demerits of the solar cookers of indequate energy back-up at night limit its operation time to sunshine hours only. However by using a few basic thermodynamic principles we can be able to remove these limitations to greater extents. These are-(a) Latent Heat Storage ,(b) Thermosiphon principle,(c) Steam Cooking Principle, (d) Heat Exchanger.

A. Latent Heat Storage:

Latent Heat is the quantity of heat stored by a material before any change of phase at a constant temperature and pressure. This Latent Heat could be used to store heat for cooking at night time. Sensible Heat cannot be used for the same purpose as the material supplying its sensible heat tends to lose its conductivity with falling temperature. The material that is used to store heat is termed as the Phase Change Material. It should have a preferably high value of Latent Heat Capacity for heat Storage. We chose Sodium Chloride as the Phase Change Material because of its high Latent Heat Capacity (492kJ/kg) and ease of availability. However its considerably high melting point of 802 °C requires a number of solar concentrators to produce the requisite heat.

B. Thermosiphon:

Thermosiphon refers to a method of passive heat exchange based on natural convection which circulates liquid without the necessity of a mechanical pump.The buoyancy of the already hot water layer is used to generate a flow of water that leads to convection. Its intended purpose is to simplify the pumping of liquid and/or heat transfer, by avoiding the cost and complexity of a conventional liquid pump.

C. Steam Cooking:

It is the use of steam as the source of heat for cooking.

The enthalpy of superheated steam is used for supplying the required amount of energy.

D. Heat Exchanger:

The Heat exchanger principle is utilized in this design so as to calculate the amount of heat dissipated at the user end. The net change in internal Energy of the steam ,at a particular mass flow rate, becomes sufficient to supply the desired amount of power to the load. This principle was employed to find out the required mass flow rate for the rated 1kW cooking.

With a given mass flow rate and input and output enthalpies of h1 and h2 the heat supplied is obtained as:

$$Q = (dm/dt) \times (h2 - h1).$$

III. CONSTRUCTIONAL OVERVIEW

The following components comprise the basic building blocks of the Night cooking solar cooker:(a)Concentrators, (b)Water Tank, (c)PCM Tower, (d)Steam Cooker, (e)Heat Distribution Pipes, (f)Condenser.

A. Solar Concentrators:

Solar concentrators are an indispensable part of any solar cooking project. Depending on the aperture they can produce different levels of heat at their Focal points. Our design requires these concentrators to focus to such an extent that they are capable to produce almost 800 °C of temperature at the absorber end. Thus we had to reject low level concentration schemes like lenses or plane reflectors for the ones like parabolic concentrators.

(1) Scheffler reflector: In a minimum of two parabolic solar concentrators are proposed in this solar cooker. The parabolic is to be made up of aluminium and its back surface is coated with black colour. This kind of concentrator is known as Scheffler concentrator. This concentrator can used to generate a very high temperature.

Experimentally,

2.7 m^2 of Scheffler concentrator can bring 1.2lts of water to boiling point within 10mins

From that we get the amount of heat in 10min= MCwdT=376.2kJ

Hence in 1 minute such a Scheffler concentrator can supply heat=37.6kJ

We will latter on Derive the heat required for a family of five to cook two traditional meals a day by taking a safe margin for losses as 10MJ.(from the calculation given below with reference to the data from FAO)

Thus the time required to store this required energy assuming proper insulation

= 10MJ/ (37.6kJ/min)=265.95min.

If we use two such concentrators then the time required is a half of the above

=265.95/2 min= 132.97 min= 2.21hrs.

Thus two 2.7m^2 Scheffler reflectors will take almost two and a half hours of sunlight.

By using four such reflectors in four sides of the absorber we may increase the cost complexity but we will also have three concrete advantages-

(i) Less time required for storing the net daily Energy requirement.

(ii) Increase the possibility of taking the used salt to molten temperatures (800 °C), as we will see later on.

(iii) Minimal requirement throughout the day for the users to track the sun for adjustment of foci.

The fact that Scheffler reflectors of 8m^2 size nowadays have shown to generate almost 1000 °C at the focus makes another option for improvement of the design.

(2) Parabolic Trough Concentrator: It employs a parabolic trough that supplies heat in a focal line. Solar power plants use parabolic troughs to make super heated steam and generate electricity because their fabrication and tracking equipment is less expensive than the dish type concentrators.

B. Water Tank:

This unit will be useful in two ways-

(1) Storing of heat exchange material that is, water for their high retention capability.

(2) Providing the starting energy required to cook in the morning when no energy is there inside the PCM.

The water tank is made up of stainless steel and having a carbon black Paint coating in the outer surface because of its high absorptance to emissivity ratio. Again sufficient glazing is also a requirement. Inside the tank there is a copper coil for better conduction of heat. The water tank is located in the focal point of a parabolic surface. During day the water tank absorbs heat and the water is converted to steam which passes through the heat exchanger of the solar cooker. The copper pipe is arranged in a coiled form to increase heat flow. This arrangement will ensure that the cooker can start in the morning itself so that the user need not wait till the PCM heats up. This provides an additional supply for day cooking.

C. PCM Storage Without Insulation:

Heat retention works the best for materials with impressive Specific Heat Capacities. But this is just the half story. While retention does depend upon Heat Capacity another factor that comes to play is conductivity. Under high temperature regions, sensible heat materials are not so good conductors.

That is why Phase Change Materials (PCM) are the best bet for Heat retention. Successfully, many designers have used Nitrate salts and acetanyline for this purpose. However, as it seems for our requirements they may not be suitable. For example Lithium Nitrate is not at all available in many regions across India, even though it may have an impressive Latent Heat.

However the Nitrate Salts have to be rejected on the ground that they are unavailable and at the same time are known to yield explosive.

This is where Sodium Chloride stands a chance because of availability. However, to be used as a Phase Change Material Sodium Chloride has to be raised to its melting point of 802°C. With a specific heat capacity of 492kJ/kg Heat retention is not a problem for Sodium Chloride.

Though achieving its molten state will be a tedious task, given that we get there we will need a highly insulated chamber to store the excess heat. By using concentrators surrounding NaCl in all four directions, we can hope to achieve this molten state within a tower like arrangement as shown below:

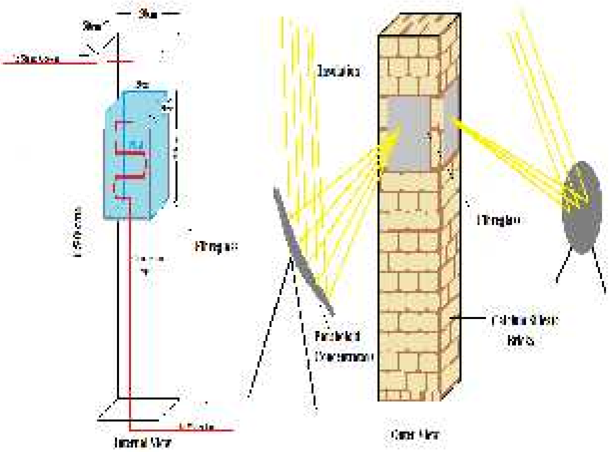

Fig.1: ***Schematic View of PCM Tower***

The Sodium Chloride will be concentrated by radiation through the fibreglass glazing material. This PCM tower is made up of Calcium Silicate bricks with reinforcement for insulation. A space for airgap is left in the chamber containing the Salt keeping in mind that NaCl will expand with temperature. After the melting is reached the molten NaCl starts storing heat in the form of latent heat which can be used later. During night time the fibre glass is covered with doors of perfectly reflecting mirrors so that no heat will be radiated through the glass after sun set. Also the airgap will act as an insulator. The conduction pipe used is made up of copper and is insulated along the tower with a fire clay cavity, except within the chamber where it's supposed to conduct.A diagram showing the insulation of the copper pipe is shown:

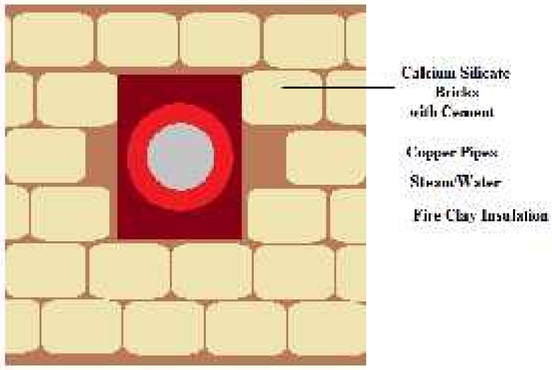

Fig.2: ***Conductor through the tower***

For a particular corner in the Salt Chamber the Airgap insulation is shown below. The Copper pipe in this section is free from the cavity to facilitate conduction for heat exchange.

The inner surface of the wall is lined by Fire Clay to resist the high temperature thus generated. The inner walls of the heat absorbing section of the PCM tower can be shown as below:

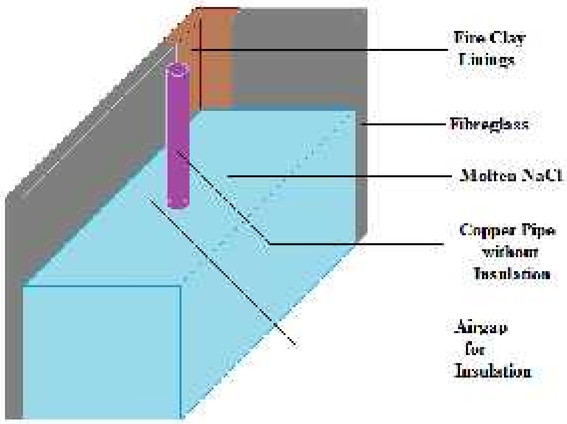

Fig.3: ***Inner Wall of the Absorbing section***

D. Cooking Unit:

The cooking unit is designed to cook various Indian foods. The design uses steam cooking mechanism. The steam comes from the solar thermal battery (PCM) through the copper pipe to the heat exchanger of the cooking vessel and supplies heat to the material to be cooked. Out of the two cooking vessel in the grill type cooking vessel the steam flows through the narrow grills and baking foods like chapatti and frying can be done.

These grills have to be corrosion resistance apart from being good conductors. The possible options for the materials to be used in this are:

- Stainless steel (Usually the most expensive and longest-lasting option, may carry a lifetime warranty)
- Porcelain-coated cast iron (The next best option after stainless, usually thick and good for searing meat)
- Porcelain-coated steel (Will typically last as long as porcelain-coated cast iron, but not as good for searing)
- Cast Iron (More commonly used for charcoal grills, cast iron must be constantly covered with oil to protect it from rusting)
- Chrome-plated steel (Usually the least expensive and shortest-lasting material)

Considering requirement stainless steel or Porcelain-coated Cast iron Grills can be incorporated. In the pot type cooker stainless steel vessel the heat exchanger is coiled around the vessel which exchange heat. This pot can also be made of earthen materials as used in traditional Indian stoves but in any case they have to be coated so as to reduce radiation losses. The inlet of the two cooking unit can be controlled by valve to regulate the supply to either of the two cooking unit. The outlet of the cooking unit is connected to a narrow pipe so that the outlet steam from the cooking vessel will be able to travel to the condenser placed just above the water tank. The junction of the two outlets is also guarder by a valve ensures the one way supply of steam. This section can be shown schematically as below:

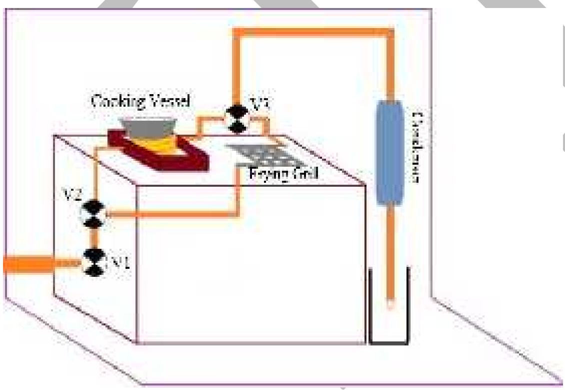

Fig.4: ***Steam Cooking Unit Schematic***

E. Circulating Pipes:

The circulating pipes are made up of copper because of their high melting point (1084°C).The pipes that are exposed to atmosphere can covered with clay and sawdust mixture having a very good thermal resistivity(11.11mK/W).The copper pipes carry the steam to the heat exchanger of the cooking vessel. The outlet water from the cooking vessel is carried through narrow pipes to the condenser.

F. Condenser:

The condenser is immediately after the cooking end to condense the steam and recycle the water. The steam coming from the outlet of the cooking vessel is transferred to the condenser and is allowed to expand and condense to water which is again supplied to the water tank.

This tank is unpressurised and has an outlet for coolant overflow. A daily maintenance of cold water is necessary from the part of the user. The volume of the condenser tank water should be sufficient to provide cooling throughout application time.

The figure below shows the condenser model:

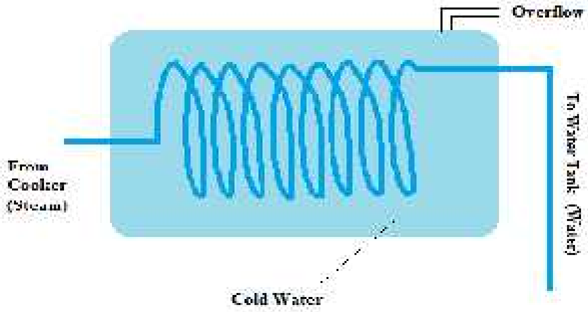

Fig.5: Condenser Unit Schematic

IV. WORKING

This model provides parallel cooking of meals in day as well as night time. In the morning when the salt is not charged, the initial heat is generated by the steam produced in Water tank due to the parabolic trough. This superheated steam is directly given to the cooking vessel for cooking purpose. After cooking the relatively low temperature steam is condensed in the condenser and water is collected in outlet.

During day time the NaCl start to charge itself thermally by the heat generated from the Scheffler reflector. All the Valves must remain closed if no cooking is going on. In the night time, the Water Tank no longer is a source. The heat of the Molten Salt is to be used for night applications. Thus the valves are opened and the heat flows through convection. While passing through the heat exchanger the water gets converted to superheated steam and passes to the heat exchanger of the cooking vessel through the insulated pipes. The heat from the steam is supplied to the food for cooking..At the time of cooking the water from the tank is regulated according to the requirement to get the desired amount of steam. There are two type of cooking vessel present, i.e., pot type and frying grill type to cook various type of food as per user requirement.

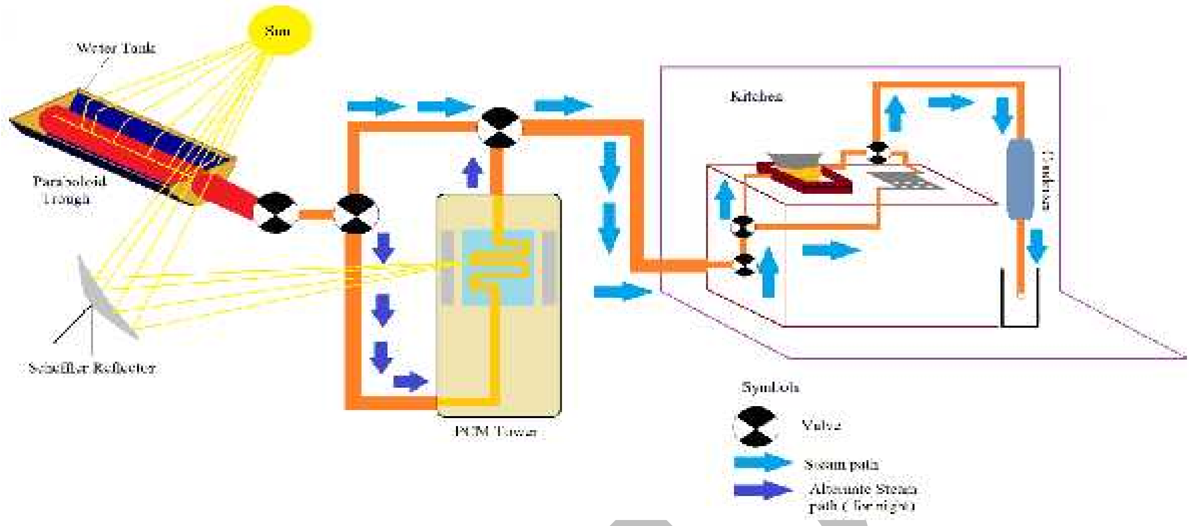

Fig.6: ***Schematic View of Solar Cooking System.***

After sunset the PCM is covered by reflecting door from the outside so that heat loss through the glass can be minimized .At the time of cooking the water from the tank is regulated according to the requirement to get the desired amount of steam. During day cooking the valve should be opened in such a way that the steam directly flow to the cooking vessel without going through the PCM. During night time the valve is operated in the reverse direction to flow the water only through the PCM.

In the day time cooking can be possible between 10am to 3pm directly from the steam produced by the parabolic trough.PCM gives a back of 14 hours after sun set. One can cook food between evening 6pm to morning 8m.So the above model provides 24 hour cooking round the clock.

This model can be representated by the Schematic Diagram and the Energy flow Diagram as shown:

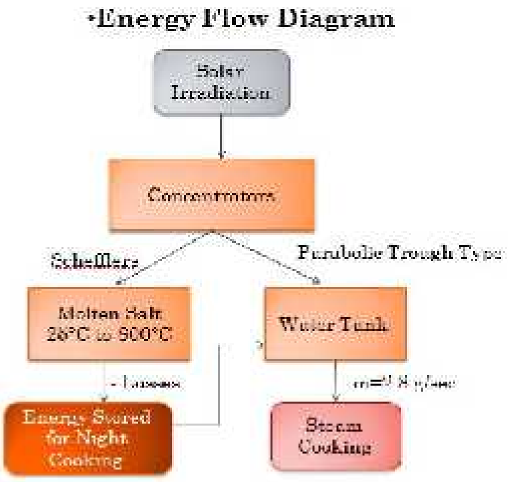

Fig.7: ***Energy Flow Diagram***

V. CALCULATIONS FOR DESIGN

The calculation of different design parameters of the solar cooker can be broadly divided into following parts:

(a)PCM Tower, (b) Steam Cooker and Steam flow rate.

A. PCM Tower Calculation

For the Sodium Chloride Phase Change Material used the Total Mass required can be calculated from the Total Energy requirement for cooking and its Latent Heat of Fusion under ideal conditions. This is given as;

$$M_{salt} = \frac{E_{cooking}}{L_f}$$

The Total Heat required by the above mass of salt to store this energy is given by;

$$Q_{salt} = M_{salt} \cdot S \cdot \Delta T + M_{salt} \cdot L_f$$

To deliver this much amount of energy the time taken by the Scheffler reflectors is found out by:

$$t_{sch} = \frac{Q_{salt}}{P_{sch}}$$

B. Steam Cooker and Steam flow rate:

The time required for cooking can be calculated from the total cooking energy requirement and the output Power of the steam cooker as below:

$$t_{cooking} = \frac{E_{cooking}}{P_{out}}$$

The Steam flow rate can be obtained from Energy balance Equation as below, by considering the Enthalpy change:

$$\int \dot{m} \cdot dt = \frac{E_{cooking}}{\Delta h_{cooking}}$$

VI. ADVANTAGES OF THE DESIGN

The advantages of the night cooking solar cooker can be summed up as below:

- Cooking beyond sunshine hours.
- Indoor cooking facility.
- Ease of availability of component materials and cost effectiveness of the same.
- Eco-friendly and no health hazards on the user.
- The water condensed, provides a source of clean drinking water or can be reused.

Within the given constraints, making a solar cooker that too with traditional means is no easy task. This design though may face greater practical difficulties when enacted but it will be robust enough in principle.

Even if it's not a complete solution to the problem of Energy efficiency but the design does add to this cause.

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